ТОПЫРАҚТАНУ ЖӘНЕ АГРОХМИЯ
ПОЧВОВЕДЕНИЕ И АГРОХИМИЯ
SOIL SCIENCE AND AGROCHEMISTRY

IRSTI 68.33.01 https://doi.org/10.52081/bkaku.2026.v77.i2.338

HUMIC SUBSTANCES IN AGRICULTURE: ENVIRONMENTAL SAFETY AND APPLICATION EFFICIENCY – A REVIEW

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Annotation. Humic substances (HS) are an essential component of soil organic matter and are considered a promising basis for the development of environmentally safe bioproducts used in sustainable agriculture. In the context of global soil degradation and the increasing demand for enhanced productivity of agroecosystems, interest in natural compounds capable of improving soil fertility and stimulating plant growth is steadily growing. This review summarizes current scientific data on the origin, structure, physical and chemical properties, as well as biological activity of humic substances, as well as their role in the functioning of soil ecosystems. It is shown that humic substances are formed during the humification of organic residues and are characterized by a complex molecular structure containing various functional groups that ensure their high chemical and biological activity. Due to their ability to participate in complexation, ion exchange, and electron transfer processes, humic substances regulate key soil processes, including nutrient cycling, carbon sequestration, soil structure formation, and detoxification of pollutants. Particular attention is given to the physiological effects of humic substances on plants. It is demonstrated that they exhibit hormone-like properties, stimulating root system development, activating metabolic processes, and increasing plant resistance to abiotic stress. In addition, humic substances enhance the bioavailability of macro- and micronutrients, improve soil water retention capacity, and promote the activity of soil microbiota. The review also examines modern methods for obtaining humic acids from natural carbon-containing materials, including chemical, mechanochemical, hydrothermal, biochemical methods, as well as process intensification techniques using ultrasound, microwaves, and electromagnetic fields. The advantages and limitations of various technologies, as well as their environmental aspects, are discussed. Thus, humic substances are considered multifunctional natural compounds with significant potential for improving soil fertility, enhancing the sustainability of agroecosystems, and developing biologically active products for agriculture. Their use opens new opportunities for the advancement of environmentally oriented agricultural technologies and for addressing current challenges in food security and environmental protection.

Keywords: humic substances, humic acids, soil organic matter, plant biostimulants, soil fertility, sustainable agriculture.

Introduction. Review of Humic Substances. Humic substances (HS) represent a complex and heterogeneous group of organic compounds formed during the decomposition of plant and animal residues in soil. They play a key role in maintaining the health of soil ecosystems by influencing soil structure, water retention capacity, nutrient cycling, and microbial activity. This review summarizes data from a wide range of peer-reviewed studies, meta-analyses, and recent advances in soil chemistry and agricultural sciences. The literature considered includes both classical works that established the fundamental chemical and biological properties of HS and contemporary studies investigating their application for improving crop productivity and the sustainability of agroecosystems. Scientific databases such as Web of Science, Scopus, and Google Scholar were used for the analysis. The selection of publications was carried out using key terms including "Humic Substances," "Humic Acids," "Fulvic Acids," "Humin," and "Organic fertilizers from HS." The review highlights the multifaceted effects of HS: they contribute to the improvement of soil structure, stimulate microbial activity, enhance plant stress tolerance, and increase nutrient uptake efficiency. Particular attention is given to their potential role in organic farming, carbon sequestration, and biodiversity conservation. The integration of historical data with recent research provides a comprehensive understanding of the importance of HS for sustainable agriculture and their environmental impacts.

Relevance of Soil Degradation Issue. Soil degradation is one of the most pressing global challenges, as it is currently estimated to affect one-third of the Earth's land surface, resulting in the loss of approximately 24 billion tons of fertile soil annually [1]. If this trend continued, it may lead to a 12% reduction in food significant increase in food prices over the next 20 years [2]. Soil degradation is associated with long-term consequences, whereas soil restoration requires the rapid implementation of cost-effective strategies [3].

Therefore, timely and economically efficient soil restoration strategies are of critical importance. One promising approach is the use of humic substances (HS), which can enhance soil carbon sequestration by stabilizing carbon in solid or dissolved forms, thereby preventing its release into the atmosphere. As part of the Paris Climate Agreement, the "4 per 1000" initiative advocates for an annual increase of 0.4% in soil carbon levels, aiming to combat climate change, improve global food security, and reduce CO_2 accumulation in the atmosphere [4]. HS, formed through the humification and carbonization of natural carbonaceous materials (NCM) such as lignite, brown coal, leonardite, and peat, plays a key role in soil ecosystems [5].

The formation of soil organic matter (SOM) under natural conditions occurs through the prolonged process of humification, where organic matter decomposes over extended periods of time [6]. However, decreasing humus content – mainly due to intensive farming and continuous fertilizer input – has led to the necessity of artificially producing humic substances (HS) in order to preserve soil fertility [7].

As the main constituent of soil organic matter, humic substances (HS) account for 60-80% of total SOM, constitute 50-80% of dissolved organic matter in aqueous environments, and about a quarter of the organic matter in groundwater [8]. These substances improve soil water-holding capacity, regulate soil macroaggregation, contribute to carbon sequestration, and influence soil microbiome dynamics. In addition, biologically active natural products, including HS, accelerate plant growth, shorten developmental periods, increase crop yields, stimulate the synthesis of phosphorus-containing and protein compounds, enhance respiration and cell proliferation, and promote biomass accumulation through intensified nutrient uptake. They also positively affect animal health by increasing weight gain and fertility and significantly stimulate the growth and reproduction of protein-producing yeasts.

The Role of Humic Substances in Sustainable Agriculture. The global agricultural sector is facing unprecedented challenges in the 22st century: according to projections, the world population will reach 9.7 billion by 2050, requiring a 70% increase in food production [9]. At the same time, agriculture must address environmental issues, cope with resource scarcity and the impacts of climate change, while maintaining the economic sustainability of farming systems.

Effective management of soil organic matter through sustainable agricultural practices— such as crop rotation, mulching, intercropping, as well as the application of artificial soil conditioners, including humic products, biochar, and biocompost—plays a key role in maintaining soil fertility and mitigating climate change impacts [2]. Practices such as crop rotation, reduced tillage, organic farming, and agroforestry contribute to improving soil health and enhancing its resilience to external stresses [10].

Recent studies emphasize the importance of integrating humic substances with organic fertilizers for sustainable soil management. This combination enhances soil fertility, improves nutrient availability, and stimulates microbial activity. In particular, the combined application of HS with compost or biochar increases the stability of soil organic matter and the efficiency of nutrient cycling, thereby positively affecting plant growth and crop yields [11,12].

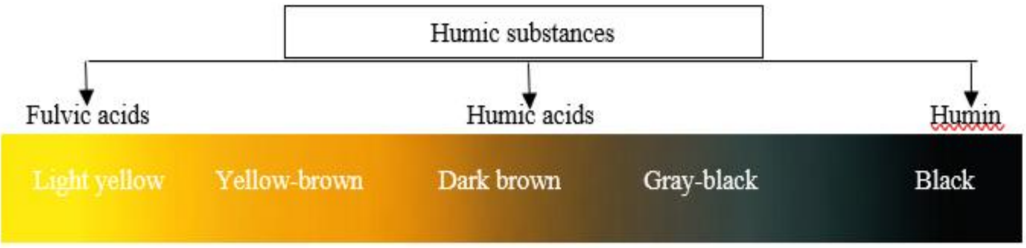
The synergy between HS and organic additives promotes the formation of stable soil aggregates, improves soil water retention capacity, reduces erosion, and enhances the bioavailability of key nutrients such as nitrogen and phosphorus, while simultaneously decreasing the washout of harmful compounds, thereby contributing to the environmental sustainability of agroecosystems [13].

Characteristics of Humic Substances. Humic substances (HS) are natural high-molecular-weight organic compounds formed during the humification of plant biomass under the influence of biological and chemical factors. The main industrial sources of humic substances include leonardite and lignite, as well as natural organic substrates (such as compost and vermicompost) [14].

Humic substances are formed as a result of the decomposition and transformation of residues of living organisms, predominantly of plant origin [15]. Once organic matter is released into the environment, its more stable components can persist due to structural irregularities and the formation of mineral complexes [16]. Humic substances (HS), formed through stochastic synthesis, represent chromogenic and structurally diverse organic materials commonly found in soils, aquatic systems, and coal-related natural deposits, including peat, leonardite, and lignite [17]. These high-molecular-weight compounds, with molecular masses ranging from 600 to 300,000 Da [18], consist of a variety of chemical components, including aromatic structures such as benzene, quinoline, pyrrole, pyridine, and furan. The structure of HS includes bridging groups such as – O – , -NH-, - N =, $-CH_2-$, and -C=C-, with predominant functional groups including carboxyl, phenolic, amino, quinone, and methoxy groups [4].

Humic substances are conventionally classified into humic acid (HA), which are soluble under alkaline conditions but insoluble in acidic media; fulvic acids (FA), which are soluble in both acidic and alkaline environments; and humin, which is insoluble in both (Figure 1). The chemical structure of HS includes aromatic rings linked to aliphatic chains, which vary depending on their origin. Fulvic acids are characterized by lower molecular weight and higher oxygen content, but lower carbon and nitrogen content compared to humic acids and humin[18].

The solubility of humic acids (HA) depends on the pH of the medium. Under alkaline conditions, HA is deprotonated, leading to the formation of hydrophilic anionic groups such as carboxylates and phenolates, which are soluble in solution. In acidic media, HA precipitates due to protonation and an increased concentration of hydrogen ions [18]. As the pH decreases, electrostatic repulsion between functional groups is minimized, leading to a more compact molecular structure and resulting in the precipitation of humic acids in acidic conditions [19].



	-	Color intensity	+	
	-	Degree of polymerization	+	
2000	-	Molecular weight	+	300 000
45%	-	Carbon content	+	62%
45%	-	Oxygen content	+	30%
1400	-	Exchange acidity	+	500
	-	Solubility degree	+	

Figure 1 – Main fractions of HS and their characteristics

Under these conditions, the hydrophobic regions of humic acids (HA) orient inward, while the hydrophilic parts interact with the surrounding environment. This behavior imparts surfactant-like properties to HA, enabling the formation of micelle-like structures that reduce surface tension. The process begins with intramolecular aggregation, followed by intermolecular aggregation, ultimately leading to the precipitation of HA under acidic conditions [18].

Depending on their source, HA contain various functional groups, including carboxyl, hydroxyl, (both aliphatic and aromatic), quinone, and amino groups [20]. The presence of carboxylic and phenolic groups confers acidic properties to HA [21]. The C/N ratio is a key characteristic of humic acids (HA). Due to microbial activity, decomposition processes, and condensation reactions with amino compounds in soil, natural HA is enriched with nitrogen compared to synthetic HA. Understanding the characteristics and differences between synthetic and natural HA is essential for their diverse applications, given the similarities in their structure and formation mechanisms [22].

Since several organic fragments present in HS participate in redox processes, donor–acceptor electron transfer mechanisms, adhesion, and pH regulation [16], HS directly induce multiple biotic and abiotic reactions, contributing to microbial respiration, enhanced soil fertility, transformation of xenobiotics, and metal bioavailability [23]. In particular, the use of HS to improve crop yield and soil quality has attracted significant attention due to the urgent need for environmentally friendly organic fertilizers as alternatives to conventional NPK-based chemical fertilizers (nitrogen, phosphorus, and potassium) [24]. Despite containing insufficient amounts of essential NPK nutrients [16], HS are widely used as soil amendments and plant growth biostimulants [24,25]. This is attributed to their ability to enhance soil organic carbon sequestration, especially in agricultural soils experiencing continuous organic matter depletion [26].

Incorporating humic substrates into the soil enhances crop yields by introducing abundant oxygen-bearing functional groups that elevate soil acidity[23]. Consequently, macronutrients-especially phosphorus-show increased bioavailability due to the greater solubility of phosphorus under acidic conditions [27,28].

HS possess high molecular weight and exhibit strong adhesive properties due to oxygen containing functionak groups, which promote soil particle aggregation and, consequently, increase crop yields [29]. Patterns of aggregation have been shown to depend on both soil type and the origin of HS [29]. Notably, HS are capable of directly stimulating plants by modulating the expression of genes and functional proteins [23]. Experimental evidence of the penetration of HS components into plant roots has been demonstrated using microautoradiography demonstrated using microautoradiography [30]. Although the precise mechanisms by which humic substances (HS) cross the root surface(rhizoplane) are not fully understood, their transport seems to depend on the molecular size distribution of HS components [23]. Once absorbed, movement from roots to shoots occurs primarily through transpiration [30]. Additionally, certain active functional proteins-including high-affinity K^+ transporter 1, phospholipase A_2, and H^+-ATPase-are known to be modulated by HS [31].

Further research is required to determine how HS components influence the activity of such enzymes; however, two plausible mechanisms can be considered. First, oxygen-containing functional groups in HS can alter the pH of the cellular microenvironment, thereby affecting the activity of membrane proteins. In particular, the alkalinization of root cell membranes induced by the $H+/NO_3-$ symporter may be neutralized by the acidity of HS [23]. Second, the non-specific adhesive properties of HS are likely to facilitate interactions with functional proteins, which may result in either activation or deactivation. This hypothesis is supported by experimental evidence demonstrating the ability of HS to physically encapsulate proteins via electrostatic interactions in vitro [16].

Humic substances (HSs) also contain inorganic components that play an important role in the formation of their structure and in their functional performance in soils. These components include minerals, metals, and various elements incorporated into the humic structure through adsorption, complexation, and co-precipitation processes.

In addition, HSs are capable of accumulating trace elements such as zinc (Zn), copper (Cu), and manganese (Mn), as well as heavy metals including lead (Pb) and cadmium (Cd), and metalloids such as arsenic (As). Through chelation processes, these elements are converted into less mobile forms, thereby reducing their bioavailability and potential toxicity in soils [32].

Studies have also demonstrated the ability of humic substances of different origins to reduce Cr(VI) to Cr(III). Peat-derived humic substances exhibit higher reductive activity, whereas coal-derived HSs are characterized by a more prolonged but less intense reduction effect [33].

Multistimulatory Effects of Humic Substances on Plant Growth and Development. In recent years, plant growth regulators–adaptogens, including humic substance (HS) – based compounds–have become widely used in agriculture. Numerous studies have demonstrated that HS exert multistimulatory effects on plant physiological processes, including seed germination, root system development, and tolerance to abiotic stress [31,34].

Humic substances act as natural growth stimulants, directly affecting cellular signaling pathways, regulating enzymatic activity, and optimizing soil–plant interactions. Unlike conventional mineral fertilizers, they provide an environmentally safe approach to enhancing crop productivity [35].

The effects of HS on plants are realized through two main mechanisms: an indirect mechanism—via modification of the physical and chemical properties of soil—and a direct mechanism—through their influence on plant physiological and metabolic processes. Studies [36] have shown that HS and their fractions positively affect both primary and secondary metabolic pathways in plants under laboratory as well as field conditions.

Humic substances have emerged as important regulators of root growth, plant development, and adaptation to environmental factors. Recent studies indicate that humic substances function as signaling molecules, influencing root system architecture, nutrient uptake efficiency, and plant stress adaptation mechanisms [37].

In addition, HS play a significant role in accelerating seed germination. Germination of several plant species, such as maize [38], Arabidopsis thaliana [39], and rice [40], is enhanced in the presence of HS. Phenolic fragments incorporated into the structure of humic substances are considered one of the key factors determining the stimulation of seed germination [38].

It should be noted that low-molecular-weight phenolic compounds, such as *p*-coumaric acid and *p*-hydroxybenzoic acid, which are widely distributed in soil, exert a pronounced inhibitory effect on seed germination by disrupting glycolysis and the oxidative pentose phosphate pathway [41], whereas polymerized phenolic compounds structurally similar to humic substances promote seed germination [39]. According to the authors, the observed contrasting effects are associated with the degree of humic substances is a critical factor controlling phenolic-induced enzyme inhibition. Moreover, inhibitory effects of humic substances on seed germination have been reported at defined concentrations [39]. As shown in studies [42,43], HS significantly promotes root growth and strengthening in agricultural crops, particularly enhancing lateral root proliferation. Three primary mechanisms have been suggested to root stimulation. The first involves hormone-like organic constituents, such as auxin-type compounds, which can trigger specific hormonal signaling pathways in plants. Auxin-like moieties have been detected within organic fractions of humic substances derived from vermicompost [42]. Nevertheless, studies employing humic substance analogues produced through the polymerization of well-characterized low-molecular-weight phenolic compounds, which lack a definitive auxin structure, indicate that the overall arrangement of functional groups within humic substances-particularly phenolic and carboxylic moieties-may play a more decisive role [39].

A more detailed analysis shows that structural characteristics associated with root initiation and growth differ. Garcia et al. reported that labile, highly functionalized organic groups are mainly involved in root initiation, whereas more stable and less functionalized fractions predominantly contribute to root elongation [44]. In addition, specific structural motifs capable of selectively enhancing root system development have been identified. In particular, the aliphatic hydroxyl group of lignin plays a key role in promoting maize seedling development without affecting germination rate [45]. Secondly, humic substances stimulate the production of nitric oxide, which in turn enhances the formation and growth of lateral roots. The observation that nitric oxide scavengers, rather than auxin pathway inhibitors, effectively suppress humic substance-induced root development suggests the involvement of auxin-independent signaling mechanisms [43]. Thirdly, an increase in the expression of proteins related to energy metabolism has been observed, indicating that enhanced metabolic activity may contribute to root cell proliferation [46]. Collectively, these two latter mechanisms suggest that nitric oxide and energy metabolism-related proteins are key biological determinants of root development. However, the specific structural components of humic substances responsible for triggering these processes remain insufficiently investigated.

Experimental studies provide further evidence of the stimulatory effects of HS on plants. Foliar application of HS solutions improved photosynthetic activity in peppermint (*Mentha piperita* L.), while the combined use of HS with chemical fertilizers and inoculation with the mycorrhizal fungus *Funneliformis mosseae* enhanced plant biochemical parameters [47]. Other studies have reported increased chlorophyll content in maize leaves following foliar application of HS under both water-deficient and optimal moisture conditions. These findings demonstrate the practical benefits of HS for improving crop productivity and resilience, as well as their positive impact on soil condition and reduction of environmental burden.

Methods for Obtaining Humic Acids. Due to their high ash and moisture content, elevated levels of volatile substances, and low calorific value, natural carbonaceous materials are of limited interest as solid fuels. However, their high content of humic substances makes them attractive as raw materials for the production of humic acids.

Technologies for the extraction of humic acids from natural carbonaceous materials comprise a range of approaches, including conventional extraction methods and those enhanced by physical intensification techniques, such as hydromechanical, ultrasonic, and electrodynamic treatments, as well as their combined applications. Additional approaches include oxidative processes, hydrothermal conversion, and mechanochemical activation [48].

To systematize existing technologies for the production of humic acids from various natural carbon-containing materials, the main methods, their underlying principles, and technological features are presented in Table 1.

Table 1 – Comparative characteristics of the main methods for obtaining humic acids from natural carbon-containing materials

Method of production	Main raw materials	Process principle	Advantages	Limitations
Alkaline extraction	Leonardite, brown coal, peat	Dissolution of humic substances in an alkaline medium followed by precipitation upon pH reduction	High yield, technological simplicity, and widespread application	Possible modification of humic substance structure and the use of chemical reagents
Acid–alkaline extraction	Peat, lignite	Preliminary acid treatment to remove mineral components followed by alkaline extraction	Production of purer humic acids	Additional process steps
Mechanochemical activation	Brown coal, leonardite	Disruption of raw material structure by mechanical action with activation of chemical reactions	Increased yield of humic acids and reduced reagent consumption	Requires specialized equipment
Hydrothermal treatment	Biomass, organic waste	Treatment of raw material with subcritical water at elevated temperature and pressure	High efficiency of organic structure disruption	High energy consumption
Biochemical method	Compost, organic waste	Biodegradation of organic matter by microorganisms with the formation of humic compounds	Environmentally safe process	Long processing time
Ultrasonic extraction	Peat, brown coal	Cavitation effects of ultrasound accelerating the breakdown of raw material structure	Intensification of the extraction process	Possible structural degradation at high power
Microwave-assisted extraction	Peat, coal	Rapid heating and structural decomposition of organic material under microwave irradiation	Reduction of extraction time	Requirement for specialized equipment
Electrochemical method	Carbon-containing materials	Oxidation of organic substrate in an electric field	Increase in the number of functional groups and yield of humic acids	Strict control of process conditions is required

Extraction processes for obtaining humic acids (HA) include acid–alkaline extraction, acid precipitation, extraction using organic solvents, and extraction employing ion-exchange resins [19]. Each of these extraction methods has both advantages and limitations. For instance, acid extraction is relatively simple and cost-effective; however, it leads to a high level of impurities in the final product and considerable atmospheric emissions, rendering it environmentally unfavorable for both research and practical applications [49]. Notably, when acid extraction is applied as a pretreatment step prior to alkaline extraction, the resulting humic acids are characterized by higher molecular weight, reduced nitrogen and carbon contents, and increased oxygen and hydrogen contents compared with those obtained through alkaline extraction alone. According to the authors, this effect is attributed to the removal of low-molecular-weight compounds during the acid pretreatment stage [50].

A leaching-acid precipitation approach is among the most commonly employed approaches for the extraction of humic acids from natural carbonaceous materials. Humic substances can be fractionated into fulvic acids (FA), brown humic acids, gray humic acids, and humin according to their solubility across different pH ranges and concentrations [51].FA are soluble over the entire pH spectrum, whereas brown and gray humic acids are soluble within the pH range of 2 to 7, while humin remains insoluble under all pH conditions [52]. A wide range of chemical reagents is utilized in these processes, including sodium and potassium hydroxides, ammonia, soda, sodium fluoride, sodium acetate, sodium oxalate, sodium pyrophosphate, ammonium oxalate, as well as organic solvents such as acetyl bromide, aqueous dioxane, furfural, and amines [53]. However, reagent-based extraction methods present notable limitations, as alkaline treatment may alter the structure of humic substances, reduce their biological and chemical activity, and disrupt their native configuration. In addition, a fraction of HS remains insoluble in water.

The mechanochemical method for humic acid (HA) extraction is based on the dispersion of humate-containing raw materials with the simultaneous incorporation of chemical reagents. Mechanical fragmentation of the feedstock increases the interfacial contact area, generates new pores and capillaries, and renews the reactive surface between phases. The addition of specifically selected reagents further enhances the yield of target compounds. Mechanochemical activation improves the reactivity of humic acids through solid-state processing using equipment such as ball mills and mechanical activators. This process leads to the formation of paramagnetic centers in natural carbonaceous materials and promotes the generation of reactive oxygen species and hydroxyl radicals on particle surfaces, cleavage of chemical bonds [54]. Ball milling modifies the catalytic transition state, thereby facilitating more complete interaction with the initial raw material. Mechanochemical activation increases the activity of HA through solid-phase treatment using devices such as ball mills and mechanical activators. This process generates paramagnetic centers in natural carbonaceous materials, producing reactive oxygen species and hydroxyl radicals on the particle surface through the cleavage of various chemical bonds [54]. Ball milling alters the catalytic transition state, ensuring complete interaction with the initial raw material. The main advantage of the mechanochemical method is the reduction in the use of chemical reagents and the acceleration of the overall process time [55].

Mechanochemical activation of humic acids using nanocatalysts represents an environmentally sustainable alternative approach that enhances humic acid activation, thereby improving their solubility and functional efficiency in agricultural applications. In such systems, conventional chemical oxidants, are replaced by engineered nanocatalysts designed to increase the yield of target products. A range of nanocatalysts has been reported, including 3D-MoS_2-HN [56], DS-Fe-N HC [40], TiO_2–WO_3 [57], Fe_3O_4/$LaNiO_3$ [58], and α-MnO_2/kaolinite [59], typically applied at low dosages (less than 1%) in combination with alkaline reagents. Nanocatalyst-assisted mechanochemical activation also enables the synthesis of nitrogen-enriched humic fertilizers, for example, via extrusion processes [40]. This strategy promotes the formation of additional functional during activation, leading to improved water retention capacity, enhanced nitrogen uptake by plants, and reduced nitrogen losses to soil and water systems.

Hydrothermal conversion is primarily based on the principle that subcritical water extraction can dissolve organic matter [60]. This method employs high-temperature subcritical water as the reaction medium, offering technical advantages such as high energy efficiency, short reaction times, high yields, and efficient product separation [61]. The process operates under subcritical conditions, where the critical temperature and pressure of water are 374°C and 22.1 MPa, respectively. Typically, hydrothermal processes are conducted at temperatures above 230°C and under high pressure (2–10 MPa), enabling efficient processing of organic waste [62]. The pressure generated by subcritical water maintains it in the liquid phase, allowing it to function as a polar organic solvent. An increase in temperature during hydrothermal processing reduces water viscosity, density, and dielectric constant, weakens hydrogen bonding, and increases its ionization constant [63]. As a result, water becomes an effective extracting solvent and a powerful catalyst capable of penetrating substrate pores. At temperatures of 200, 300, 370, and 500°C, the solubility of water becomes comparable to that of methanol, acetone, methylene chloride, and hexane at 25°C. As the temperature decreases below the critical point, the density and dielectric constant of water decrease, while the dissociation constant (Kw) reaches a maximum at approximately 250°C [63]. The reduction in dielectric constant lowers water polarity, facilitating the dissolution of nonpolar polymers. The weakening of hydrogen bonds increases the ionic product and dissociation of water, leading to the formation of higher concentrations of hydronium (H_3O^+) and hydroxide (OH^-) ions. Under hydrothermal conditions, the main reactions include intramolecular hydrolysis and dehydration, decarboxylation (resulting in CO_2, amines, and hydrocarbons), deamination (yielding NH_3 and organic acids), as well as condensation, aromatization, and polymerization processes (conversion of alkanes and alkenes into hydrochar) [64]. The formation of CO_2 during hydrothermal carbonization, accounting for approximately 2% of total carbon, also contributes to increased pressure. However, increasing the alkalinity of the process can suppress the formation of gaseous products to nearly zero, retaining carbon in the solid and liquid phases [65]. Hydrothermal treatment can be applied to disrupt the macromolecular structure of natural carbonaceous materials and increase the number of oxygen-containing functional groups, followed by the extraction of humic acids [66].

Biochemical methods are based on the alkaline extraction of humic substances (HS) from soil, followed by purification using microorganisms. Study [67] describes a method for producing liquid humic fertilizers through the bacterization of HS with microbial strains capable of modifying organic matter and degrading the internal structure of peat or vermicompost. Various microorganisms have been used for the extraction of humic acids from natural carbonaceous materials, including Aspergillus oryzae, Polyporus versicolor, Bacillus, Streptomyces flavus, Aspergillus flavus, Streptomyces fulvissimus, Penicillium, Trichoderma citrinoviride, Poria monticola, fungal culture M13, and MWI fungi [68–71]. The biodegradation of natural carbonaceous materials involves three main stages: solubilization, depolymerization, and utilization [72]. Solubilization occurs in an alkaline medium as a non-enzymatic process, whereas depolymerization proceeds enzymatically at pH values below 6 [68]. The efficiency of solubilization, largely dependent on oxygen availability, is a key factor in microbial decomposition [73]. Therefore, oxidizing agents are typically used as a pretreatment step to increase the degree of oxidation of the raw material, with nitric acid (HNO_3) being particularly effective in enhancing microbial solubilization and increasing the yield of humic acids [73]. In biological activation processes, the solubilization of natural carbonaceous materials, dissolution of HS in water and alkaline media, and nutrient enrichment are considered key indicators for evaluating the efficiency of HA production [74]. Surfactants and oxidants may be applied to improve biological activation [69]. For example, the combined use of Tween-80 as a surfactant and engineered strains of Phanerochaete chrysosporium *and* Trametes versicolor enhanced the biosolubilization of weathered coal while simultaneously reducing the molecular weight of humic substances [75]. Overall, microbial methods for the activation of humic substances face several limitations, including insufficient development of strain production technologies, long processing times, low yields, and poor solubility of the resulting humic substances [76].

To address challenges such as low reaction rates, multistage processing, high operating temperatures, and limited mass and heat transfer efficiency, *process intensification methods* have been proposed to enhance extraction efficiency and reduce energy consumption in the production of humic acids (HA). Various intensified extraction techniques, including ultrasound, microwave irradiation, hydrodynamic cavitation, electrical discharge, as well as electric and electromagnetic fields, have been investigated in studies [77–80]. For example, HA extraction from peat using ultrasonic treatment with NaOH has been reported [81]; microwave-assisted extraction employing H_2O_2 has been applied for the production of fulvic acids (FA) from brown coal (Fig. 2A) [82]; microwave extraction using a KOH–urea system has been utilized to obtain humic substances from natural carbonaceous materials [83]; and electrical discharge methods have been employed for the extraction of humic substances from peat [84].

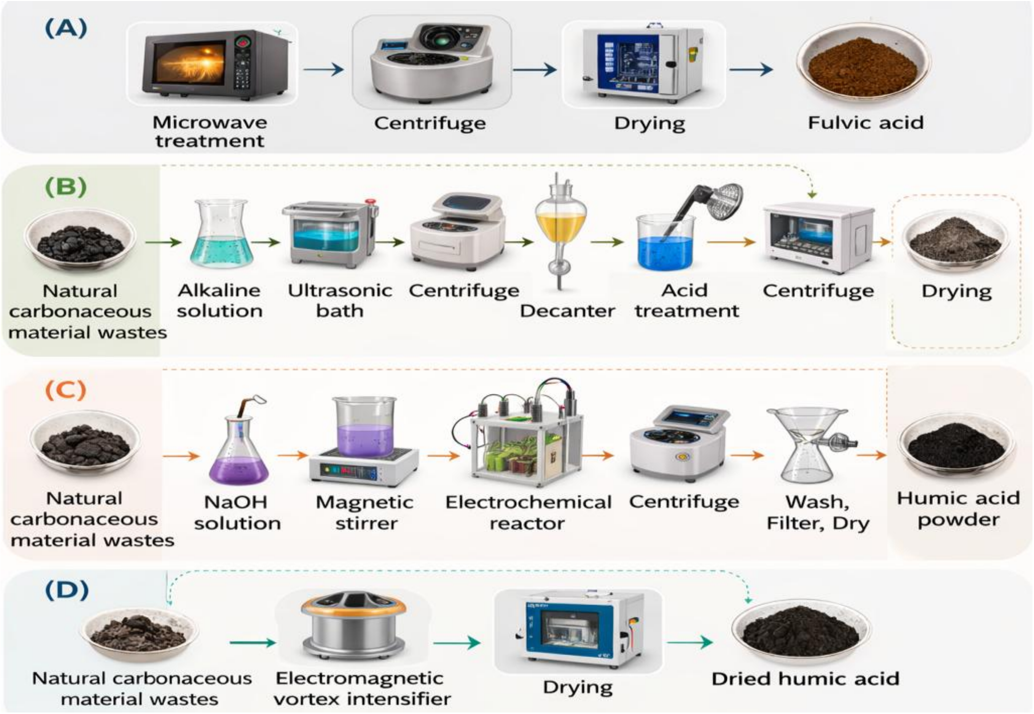


Figure 2 – Production of HA from natural carbonaceous materials using process intensification methods: (A) microwave-assisted extraction using H_2O_2; (B) integration of ultrasound with oxidizing agents; (C) combined ultrasonic treatment and extraction; (D) application of an electromagnetic vortex activator with ferromagnetic particles.

Among process intensification techniques, ultrasound has demonstrated high efficiency in improving the extraction of humic substances, particularly the hydrophobic fraction of fulvic acids. However, prolonged exposure and high ultrasonic intensity may adversely affect extraction performance [85]. Ultrasonic treatment generates shock waves and microjets, which enhance mixing, induce cavitation, and promote the formation of highly reactive species, including hydroxyl radicals, hydrogen peroxide (H_2O_2), and ozone, all characterized by strong oxidative potential. The improvement in humic acid (HA) extraction under ultrasonic treatment attributed to the increased number of active sites saturated with potassium ions (K^+), formed during KOH treatment. This facilitates HA dissolution in the liquid phase through the disruption of hydrophobic interactions and hydrogen bonding, as well as through improved chemical diffusion and mass transfer processes [86].

The combination of ultrasound with oxidizing agents represents an effective strategy for the production of humic acids (HA) and fulvic acids (FA) from natural carbonaceous materials, as illustrated in Fig. 2B. This approach not only enhances HA yield but also shortens processing time and reduces the required concentration of oxidants [86]. Ultrasound promotes the generation of OH radicals, which attack the molecular structure of the substrate and incorporate oxygen into the HA structure, enriching it with active functional groups. Moreover, this method does not involve direct CO_2 emissions, making it an environmentally friendly alternative for converting natural carbonaceous materials into humic substances. Ultrasonic treatment induces cavitation, leading to significant particle size reduction and facilitating the release of water-soluble organic compounds into the liquid phase. The humic substances transferred into the liquid phase exhibit elevated physiological activity and enhanced reactivity in subsequent hydrothermal synthesis processes [87]. Ultrasonic extraction is typically carried out using specialized devices in which both dispersion and extraction of humic substances from humate-containing raw materials.

One of the promising approaches for the production of humic acids is the application of electric and electromagnetic fields. The electric field generates an oxidative environment at the anode, enabling intensive interaction with the substrate (Fig. 2C). During treatment, substrate particles interact with the electrode surface, initiating oxidation reactions that partially suppress the oxygen evolution reaction at the anode. The established oxidative conditions promote the degradation of the macromolecular structure of the substrate through the cleavage of chemically active bonds, accompanied by the formation of oxygen-containing functional groups, including nitro and hydroxyl groups. This process leads to the formation of oxidation products, among which humic acids are of primary importance. Furthermore, electrochemical extraction facilitates the transformation of benzene and condensed aromatic structures into phenolic hydroxyl and quinone groups. The increase in oxygen-containing functional groups within humic acids enhances their solubility in alkaline media and contributes to a higher yield of the target product. Due to the high oxidative potential of the electrochemical system, bioresources with low initial humic acid content, such as compost and peat, can also be effectively processed, resulting in a significant increase in humic acid yield [88]. In electrochemical HA production methods, moderate oxidation is required to achieve optimal yields; therefore, intensification of electrochemical oxidation under controlled conditions is essential [89]. Electrode materials and the applied voltage play a crucial role in determining the efficiency of humic acid (HA) production in electric field-based processes. A range of anode materials, including Cu, Ni, Pb, and Pt, have been investigated, resulting in the formation of HA along with by-products such as oxygen (O_2), carbon dioxide (CO_2), and minor amounts of carbon monoxide (CO).

Humic acids can also be synthesized from various raw materials using electromagnetic field technologies, such as vortex layer devices (Fig.2D). In this approach, the substrate is combined with water at a moisture content of 75-95% and exposed to strong ferromagnetic and hydromechanical forces. These forces induce intensive particle collisions, reducing their size to below 15 μm, with more than 80-90% of particles reaching this range. Such treatment leads to structural disruption of the substrate and facilitates the release of humic acids. The process can be conducted both in the presence and absence of alkaline or oxidizing reagents.

The use of electromagnetic systems incorporating a vortex layer and ferromagnetic elements enhances reaction kinetics, increasing reaction rates by 1.5-2 times, while simultaneously decreasing reagent consumption and energy requirements by around 20%. During processing, the temperature is typically maintained within the range of 60-90°C. This method is effective for extracting humic acids (HA) and fulvic acids (FA) from a variety of sources, including peat, sapropel, compost, vermicompost, brown coal, and leonardite, achieving yields of up to 19 and 30.8 g/L, respectively. The advantages of this technique include the formation of nanoscale particles that prevent clogging of spray nozzles, relatively low energy consumption (approximately 9.5 kWh, with a specific energy demand of 1.9 kWh/m^3), and the use of compact equipment that can be readily integrated into existing fertilizer production systems.

Hydromechanical, cavitation, and acoustic effects are effectively utilized in rotary pulsation devices and hydrodynamic cavitators [90–92]. Under physical treatment conditions, hydrodynamic and hydroacoustic forces enable the extraction of humic substances (HS) from raw materials without the use of chemical reagents. This approach enhanced the physiological activity of humic products while maintaining a neutral pH in the resulting HS solution. Consequently, reagent-free extraction methods allow the production of chemically pure and environmentally sustainable products. Typically, HS extraction is performed in stirred reactors under elevated temperature and pressure, accompanied by high flow velocities of the extractant around solid particles [93].

Despite the generally lower yields of reagent-free extraction of HS into water compared to conventional chemical methods, the obtained products, containing humic acids (HA) and fulvic acids (FA)-are of considerable interest due to preservation of water-soluble HS in their native, unmodified state. To improve the efficiency of reagent-free extraction, preliminary particle size reduction of the raw material is required. The application of hydromechanical and hydroacoustic methods is considered a promising approach, as treatment of humate-containing suspensions results in particle size reduction and structural modification of the material, thereby significantly facilitating the release of target compounds from the raw material matrix.

Application of Humic Substances in the Agro-Industrial Sector. Humic substances, particularly humic acids (HA), are extensively applied in agricultural and industrial practices due to their complex chemical structure, the presence of reactive functional groups, and their high functional efficiency [94]. They contribute to improved soil fertility by enhancing soil aggregation, structural stability, and porosity, thereby facilitating water infiltration, retaining nutrients, and promoting the chelation of micronutrients [4]. In addition, HA positively influences soil properties by increasing water-holding capacity, permeability, tolerance to salinity, cation exchange capacity, nutrient assimilation, and the availability of soluble phosphorus [95]. In addition, humic acids play a significant role in carbon sequestration processes by stimulating photosynthetic activity and increasing microbial diversity. They enhance cell membrane permeability, serve as an energy source for microbial respiration, reduce competition for nutrients, and support the proliferation of key soil microbial groups, including Acidobacteria, Actinobacteria, and Bacteroidetes [16]. HA is also actively in the remediation of soil contaminated with heavy metals and organic pollutants, decreasing their toxicity and bioavailability through mechanisms such as electrostatic adsorption, complex formation, ion exchange, reduction, hydrogen bonding, van der Waals interactions, charge transfer, and hydrophobic interactions [96].

Humic acids stimulate plant growth by regulating plasma membrane transport proteins, enhancing nutrient uptake and metabolic processes, and promoting root cell division and elongation. Their low-molecular-weight fractions exhibit hormone-like activity by influencing molecular signaling pathways [6]. The presence of oxygen-containing functional groups in HA increases plant resistance to diseases by inhibiting pathogenic microorganisms due to their antimicrobial properties [95]. Furthermore, phenolic groups in HA act as antioxidants, scavenging free radicals and protecting plants from oxidative stress.

Under alkaline conditions, carboxyl groups demonstrate pronounced antioxidant and anti-inflammatory properties, whereas quinone structures facilitate plant recovery through the generation of reactive oxygen species (ROS) [2]. Aromatic components of himic acids (HA), characterized by O/C ratios of 0.2-0.4 and H/C ratios of 0.5-1, are associated with enhanced plant tolerance to stress factors, including diseases, and with the activation of defense mechanisms. Carbonyl C=O functionalities present in carboxyl, hydroxyl, and quinone groups contribute to the inhibition of pathogenic microorganisms [97].

The interdependence between chemical composition, physicochemical properties, molecular structure, and the physiological activity of humic acids, as well as their functional characteristics, has been extensively investigated in studies [25,44,98–104].

The physiological activity of HA is strongly influenced by their origin and the distribution of functional groups. Humic acids derived from natural carbonaceous materials typically exhibit higher molecular weight, lower carboxyl group (—COOH) content, and higher aromatic hydroxyl (Ar—OH) content. In contrast, soil-derived HA is characterized by a higher abundance of acidic functional groups, lower molecular weight, reduced aromaticity, lower C/N ratios, and increased—COOH content [18]. Functional groups such as phenolic hydroxyl, carboxyl, and carbonyl groups play a crucial role in interactions with clay minerals, metal ions, and hydrated oxides [105], thereby governing nutrient retention and release processes [96]. For instance, HA interacts with clay minerals through van der Waals forces, hydrogen bonding, electrostatic interactions, and cation bridging, leading to the formation of stable organo-mineral complexes that enhance soil aggregate stability [95].

Thus, the application of humic acids (HA) in agricultural systems enhances soil fertility and contributes to increased crop productivity [106].

Humic acids (HA) are characterized by amphiphilic, polymeric, and hydrophilic properties, along with pronounced complexation, ion-exchange, redox, and electron-transfer capacities, which arise from the presence of phenolic, hydroxyl, carboxyl, and quinone functional groups [107]. These characteristics largely determine the bioactivity of HA and their ecological functions in soil and aquatic systems, contributing to soil health and environmental stability [108]. Quinone groups are involved in the generation of reactive oxygen species (ROS), while phenolic and carboxylic groups tend to deprotonate under neutral and alkaline conditions, which underpins many of their agricultural applications. Phenolic and quinone groups act as key electron donation and acceptance, acting as active sites that regulate electron transfer processes in soil bioelectrochemical systems [109]. The hydrophilicity of HA, along with the presence of hydroxyl and carboxyl groups, promotes soil particle aggregation and enhances soil stability [4]. This, in turn, improves soil permeability and water-holding capacity [8]. Carboxyl and phenolic hydroxyl groups in humic acids (HA) are capable of forming complexes with metal ions, which modifies their activity and solubility, decreases their mobility and toxicity, and promotes the release of nutrients, ultimately enhancing soil fertility [2]. HA also exhibits ion-exchange capacity, whereby negatively charged surfaces exchange ions with cations, enhancing nutrient retention and soil fertility [95]. Moreover, the acidic functional groups of HA are able to dissociate hydrogen ions and interact with multivalent cations present on clay surfaces, leading to the formation of HA-metal-clay complexes [8]. These interactions improve key soil physical properties, such as water-holding capacity, aeration, infiltration, and porosity, thereby increasing the availability of essential mineral nutrients for plant growth [110]. Furthermore, oxygen-containing functional groups in HA stimulate the decomposition of organic matter, which enhances overall biological activity in the soil [6].

In addition to their agricultural applications, humic acids (HA) are widely used across various industrial sectors (Figure 2). They are employed as additives for fluid loss control and as emulsifiers in water- and oil-based drilling fluids, contributing to viscosity reduction and gel strength regulation [111,112]. HA also functions as a liquefying agent, deflocculant, dispersant, and rheology modifier [113]. They are also incorporated into various formulations to adjust the structure and characteristics of gels, including those used in soaps and organoclay-based lubricants [112,113]. In construction-related applications, HA contributes to controlling the stability, density, and sedimentation behavior of concrete, and is also utilized in leather processing, woodworking industries. Additionally, they enhance the mechanical properties of cementitious and ceramic materials [111]. In the pulp and sector, humic acids are employed as coloring agents, durability enhancers, and protective additives that limit the infiltration of harmful substances into wastewater. They are particularly used in the production of dark-colored paper in combination with oils, waxes, and resins, and function as modifiers of hydrophobic agents and barrier coatings. Overall, HA serves as a black pigment, filler, functional modifier (in asphalt, oil, wax, resin-based systems), and as agents that reduce the penetration of non-aqueous liquids in specialty paper manufacturing [113].

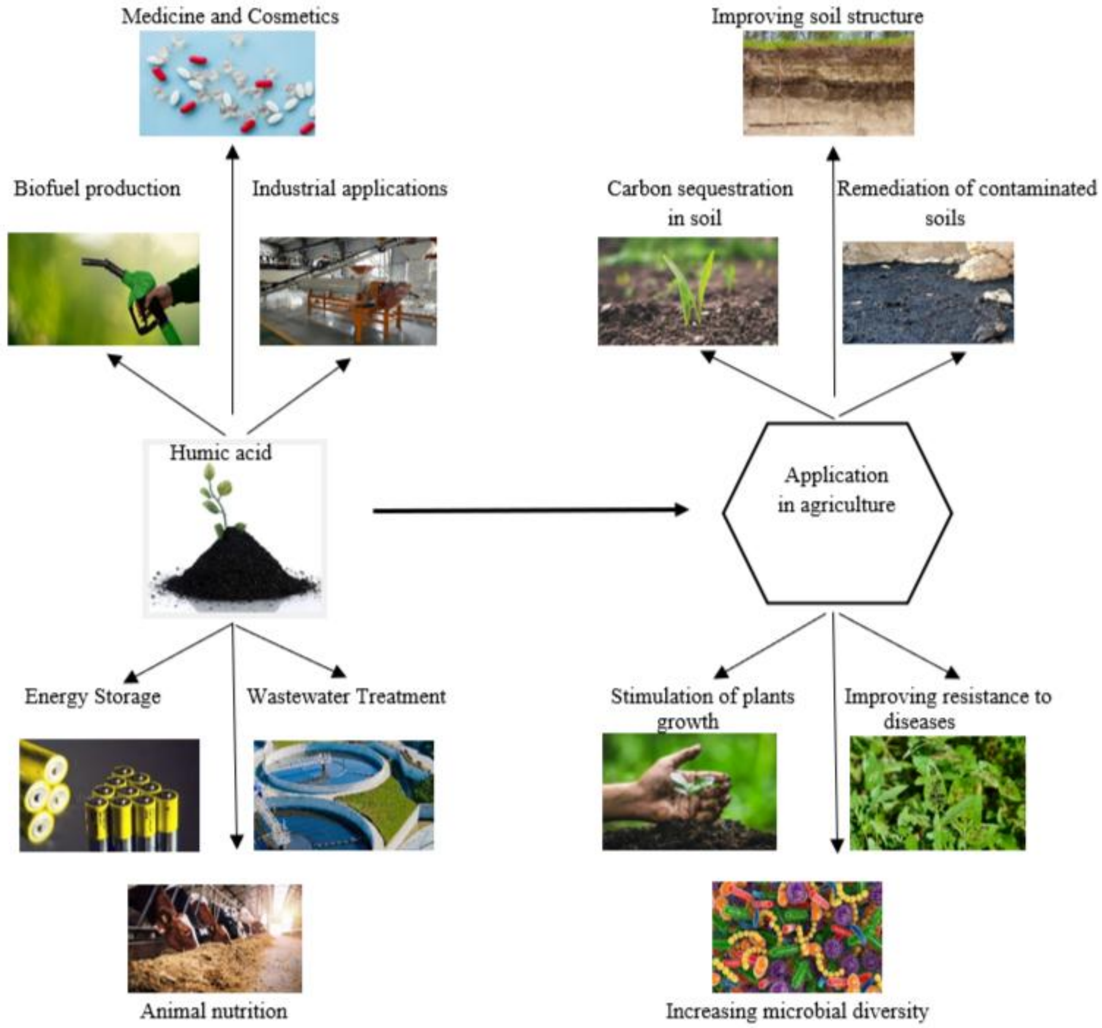


Figure 3 –Applications of humic acids (HA) in industry and agriculture

Humic acids (HA) have found broad application beyond traditional used, including roles in biofuel production (such as biohydrogen, bioethanol, biogas, and biodiesel) as catalytic agents [114–121], in environmental remediation and wastewater treatment [122,123], in advanced energy systems such as sodium/lithium-ion batteries and supercapacitors [124–126], as well as in medical, healthcare, and cosmetic industries [127,128], and as feed additives in animal nutrition [129–133].

Within biofuel production, particularly in biomass pretreatment for bioethanol generation, HA functions as an effective surfactant, delignifying agent, and solvent. For example, the addition of 30 g/L of HA during wheat straw pretreatment increased lignin removal from 16.6% to 35.6%, which consequently enhanced enzymatic hydrolysis efficiency from 64.9% to 78.2% [114]. This improvement is mainly associated with the structural similarity between HA and lignin, both of which contain polar functional groups (e.g., hydroxyl, phenolic, and carboxyl groups) along with nonpolar aromatic structures. Under alkaline conditions, hydrogen bonding between HA and lignin promotes the formation of covalent linkages through esterification reactions [114]. Moreover, due to their surfactant and catalytic behavior, HA can simplify the bioethanol production process by improving filtration efficiency and reducing the need for conventional steps such as precipitation and centrifugation [121]. In anaerobic digestion processes for biogas generation, HA exhibits both stimulatory and inhibitory effects depending on the stage, including hydrolysis, acidogenesis, and methanogenesis. Their functionality is diverse, as they may act as surfactants, binding agents, terminal electron acceptors, electron shuttles, organic complexing agents, and pH regulators [117–119]. Moreover, HA indirectly affects anaerobic fermentation by modulating the bioavailability, transformation, and biological activity of external contaminants, including heavy metals, organohalogen compounds, microplastics, and antibiotics [116].

Humic acids (HA) are distinguished by their amphiphilic architecture, negatively charged surfaces, amorphous aliphatic domains, and pronounced redox properties, which collectively enable them to function as effective electron shuttles, facilitating electron transfer from microorganisms to oxidized organic contaminants and metal ions [123]. This property underlies their potential application in the remediation of contaminated soil and water systems using HA.

Recent studies indicate that humic acids have significant commercial value and considerable potential for application across various industrial sectors. However, the natural formation of HA is a slow process, resulting in structural heterogeneity and compositional variability, which limits their broader utilization. The content of HA extracted from different natural carbonaceous materials is limited and strongly dependent on the geographical origin of the raw material, making it insufficient to meet the growing global demand. Furthermore, natural carbonaceous resources used for HA production are non-renewable, and their reserves are gradually declining, while high-quality sources are becoming increasingly difficult to access. Therefore, the development of novel methods for the synthetic production of HA with high yield and efficiency remains a critical challenge for researchers.

Conclusion. In conclusion, humic substances (HS), including humic acids, fulvic acids, and humin, represent multifunctional natural compounds with significant potential for application in modern agriculture. Their involvement in the regulation of soil and biological processes, as well as their ability to act as plant growth biostimulants, underpins their importance in enhancing agroecosystem productivity. Numerous studies demonstrate that the application of humic-based products improves nutrient uptake, stimulates root system development, and increases plant resistance to both abiotic and biotic stresses. In addition, humic substances exert a complex positive effect on soil properties, including the improvement of soil structure, enhancement of microbial activity, and increased bioavailability of macro- and micronutrients. However, despite the substantial body of accumulated research, the full potential of humic substances remains unrealized. Their practical application is still limited due to the high variability in composition depending on raw materials and extraction methods, the lack of standardized quality criteria, and insufficient reproducibility of results. A major scientific challenge remains the absence of a unified concept describing the molecular organization of humic substances, which are currently regarded as dynamic supramolecular systems. Another limitation is the insufficient understanding of their mechanisms of action at the molecular and cellular levels. In particular, deeper insights are required into their effects on plant signaling pathways, hormone-like activity, and nutrient transport processes. In the context of global environmental challenges, including soil degradation and climate change, humic substances are gaining increasing importance as a key component of sustainable and low-carbon agricultural technologies. Their ability to participate in the stabilization of soil organic carbon and to enhance resource-use efficiency makes them a promising tool for the transition toward environmentally sustainable agricultural production.

Future research should therefore focus on the standardization of humic products, the development of advanced methods for their molecular characterization, and the design of scientifically grounded and technologically efficient approaches for their application. Thus, humic substances possess substantial potential for integration into modern agrotechnologies; however, their realization requires a comprehensive interdisciplinary approach aimed at overcoming existing scientific and practical limitations.

Acknowledgment. The research was carried out under the Program-targeted financing of the Ministry of Science and Higher Education of the Republic of Kazakhstan for 2024-2026, BR24993105 «Creation of a Biotechnological R&D Center for the Development and Commercialization of Agricultural Products and Technologies».

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ГУМИНДІ ЗАТТАРДЫҢ АУЫЛ ШАРУАШЫЛЫҒЫНДАҒЫ ҚОЛДАНЫЛУЫ: ЭКОЛОГИЯЛЫҚ ҚАУІПСІЗДІК ЖӘНЕ ҚОЛДАНУ ТИІМДІЛІГІ – ШОЛУ

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Аңдатпа. Гуминді заттар (ГЗ) топырақтың органикалық затының маңызды құрамдас бөлігі болып табылады және тұрақты ауыл шаруашылығында қолданылатын экологиялық қауіпсіз биопрепараттарды әзірлеудің перспективалы негізі ретінде қарастырылады. Топырақтың жаһандық деградациясы және агроэкожүйелердің өнімділігін арттыру қажеттілігінің артуы жағдайында топырақ құнарлылығын жақсартуға және өсімдіктердің өсуін ынталандыруға қабілетті табиғи қосылыстарға қызығушылық артып келеді. Осы шолуда гуминді заттардың шығу тегі, құрылымы, физико-химиялық қасиеттері және биологиялық белсенділігі туралы заманауи ғылыми деректер жинақталып, сондай-ақ олардың топырақ экожүйелерінің қызметіндегі рөлі қарастырылған. Гуминді заттардың органикалық қалдықтардың гумификациясы процесінде түзілетіні және әртүрлі функционалдық топтарды қамтитын күрделі молекулалық құрылымымен сипатталатыны, бұл олардың жоғары химиялық және биологиялық белсенділігін қамтамасыз ететіні көрсетілген. Гуминді заттар кешен түзу, ион алмасу және электрондарды тасымалдау процестеріне қатысу қабілетінің арқасында топырақтағы негізгі процестерді реттейді, оның ішінде қоректік элементтердің айналымы, көміртекті секвестрлеу, топырақ құрылымының қалыптасуы және ластаушы заттарды детоксикациялау бар. Гуминді заттардың өсімдіктерге физиологиялық әсеріне ерекше назар аударылған. Олардың гормонға ұқсас қасиеттер көрсете алатыны, тамыр жүйесінің дамуын ынталандыратыны, метаболизмдік процестерді белсендіретіні және өсімдіктердің абиотикалық стресс факторларына төзімділігін арттыратыны көрсетілген. Сонымен қатар, гуминді заттар макро және микроэлементтердің биожетімділігін арттыруға, топырақтың су ұстау қабілетін жақсартуға және топырақ микробиотасының белсенділігін күшейтуге ықпал етеді.

Шолуда сондай-ақ табиғи көмңртекқұрамды материалдардан гумин қышқылдарын алудың заманауи әдістері қарастырылған, оның ішінде химиялық, механохимиялық, гидротермалдық, биохимиялық әдістер, сондай-ақ ультрадыбыс, микротолқындар және электромагниттік өрістерді қолдану арқылы процестерді қарқындату тәсілдері қамтылған.Әртүрлі технологиялардың артықшылықтары мен шектеулері, және олардың экологиялық аспектілері көрсетілген.

Осылайша, гуминді заттар топырақ құнарлығын арттыруға, агроэкожүйелердің тұрақтылығын қамтамасыз етуге және ауылшаруашылығына арналған биологиялық белсенді препараттарды әзірлеуге елеулі әлеуетке ие көпфункционалды табиғи қосылыстар ретінде қарастырылады. Оларды қолдану экологиялық бағытталған егіншілік технологияларын дамытуға және қазіргі заманғы азық-түлік қауіпсіздігі мен қоршаған ортаны қорғау мәселелерін шешуге жаңа мүмкіндіктер ашады.

Тірек сөздер: гуминді заттар, гумин қышқылдары, топырақтың органикалық заты, өсімдік биостимуляторы, топырақ құнарлылығы, тұрақты ауыл шаруашылығы.

ГУМИНОВЫЕ ВЕЩЕСТВА В СЕЛЬСКОМ ХОЗЯЙСТВЕ: ЭКОЛОГИЧЕСКАЯ БЕЗОПАСНОСТЬ И ЭФФЕКТИВНОСТЬ ПРИМЕНЕНИЯ – ОБЗОР

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Аннотация. Гуминовые вещества (ГВ) являются важным компонентом почвенного органического вещества и рассматриваются как перспективная основа для разработки экологически безопасных биопрепаратов, применяемых в устойчивом сельском хозяйстве. В условиях глобальной деградации почв и роста потребности в повышении продуктивности агроэкосистем возрастает интерес к природным соединениям, способным улучшать плодородие почв и стимулировать рост растений. В данном обзоре обобщены современные научные данные о происхождении, структуре, физико-химических свойствах и биологической активности гуминовых веществ, а также рассмотрена их роль в функционировании почвенных экосистем. Показано, что гуминовые вещества образуются в процессе гумификации органических остатков и характеризуются сложной молекулярной структурой, содержащей различные функциональные группы, обеспечивающие их высокую химическую и биологическую активность. Благодаря способности участвовать в процессах комплексообразования, ионного обмена и переноса электронов, гуминовые вещества регулируют ключевые процессы в почве, включая круговорот питательных элементов, секвестрацию углерода, формирование почвенной структуры и детоксикацию загрязняющих веществ. Особое внимание уделено физиологическому воздействию гуминовых веществ на растения. Показано, что они способны проявлять гормоноподобные свойства, стимулируя развитие корневой системы, активируя метаболические процессы и повышая устойчивость растений к абиотическим стрессам. Кроме того, гуминовые вещества способствуют повышению биодоступности макро- и микроэлементов, улучшению водоудерживающей способности почвы и активизации почвенной микробиоты. В обзоре также рассмотрены современные методы получения гуминовых кислот из природных углеродсодержащих материалов, включая химические, механохимические, гидротермальные, биохимические и методы интенсификации процессов с применением ультразвука, микроволн и электромагнитных полей. Показаны преимущества и ограничения различных технологий, а также их экологические аспекты. Таким образом, гуминовые вещества рассматриваются как многофункциональные природные соединения, обладающие значительным потенциалом для повышения плодородия почв, устойчивости агроэкосистем и разработки биологически активных препаратов для сельского хозяйства. Их использование открывает новые возможности для развития экологически ориентированных технологий земледелия и решения современных проблем продовольственной безопасности и охраны окружающей среды.

Ключевые слова: гуминовые вещества, гуминовые кислоты, почвенное органическое вещество, биостимуляторы растений, плодородие почвы, устойчивое сельское хозяйство.